

# Evaluation of the Neutron Background in a Direct WIMP Detector with Neutron Veto System Based on Gd-doped Liquid Scintillator

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## Abstract

A direct WIMP (Weakly Interacting Massive Particle) detector with a neutron veto system is designed to better reject neutrons. Two experimental configurations are studied in the present paper: one is for an Xe detector enclosed in a Gd-loaded scintillator and the other one is for an Xe detector placed inside a reactor neutrino detector. The Gd-doped liquid scintillator (or the neutrino detector) is used as a neutron veto device. The neutron backgrounds for the two experimental designs have been estimated using Geant4 simulations. The results show that the neutron backgrounds can decrease to  $O(0.1)$  events per year per tonne of liquid Xenon. We calculate the sensitivities to spin-independent WIMP-nucleon elastic scattering. An exposure of one tonne  $\times$  year could reach a cross-section of about  $6 \times 10^{-11}$  pb.

**Keywords:** Dark matter detector, Gd-doped liquid scintillator, Neutron background

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## 1 Introduction

It is found by the five year WMAP (the Wilkinson Microwave Anisotropy Probe) data combined with the measurements of Type Ia supernovas and baryon acoustic oscillations that the Universe is made up of 4.6% baryonic matter, 22.8% dark matter and 72.6% dark energy[1]. This means that about 83% of the matter in the Universe is unknown and called dark matter. Weakly Interacting Massive Particles (WIMPs), predicted by extensions of the Standard Model of particle physics, are a class of candidates for dark matter[2]. They are distributed in the surrounding halo of our galaxy. A WIMP halo of our galaxy with a local density of  $0.3 \text{ GeV}/\text{cm}^3$  is assumed and its relative speed to the Sun is  $230 \text{ km}/\text{s}$ [3].

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There is only weak interaction (and gravity) between WIMPs and baryonic matter, so their direct detection is very challenging. WIMPs can be directly detected through the measurement of nuclear recoils induced by their elastic scattering off target nucleus. Signals caused by interactions between WIMPs and nucleus can be measured by ionization detectors, scintillation detectors or phonon detectors. The background of this detection is made up of electron recoils produced by  $\gamma$  and  $\beta$  particles and nuclear recoils produced by neutrons. To reduce more background events due to electron recoils, a hybrid detector has been employed in the measurement of direct dark matter signatures. For example, these signatures can be detected through ionization and scintillation in the XENON10 experiment[4] and also through ionization and phonon in the CDMSII experiment[5]. The electron recoil contamination can decrease to less than  $10^{-6}$  with hybrid detectors[5, 6, 7]. However, it is very difficult to discriminate between nuclear recoils induced by WIMPs and by neutrons. This discrimination is one of the most important tasks in direct dark matter searches.

The cross-sections of neutron-nuclei interactions are much larger than those of WIMP-nuclei, so the multi-interactions between neutrons and detector components are applied to tag neutrons and thus separate WIMPs from neutrons. In the ZEPLINIIII experiment, the 0.5% Gd doped hydrocarbon material is used as the neutron veto device. This device is used to tag neutrons, and the veto efficiency is about 70%-80%[8, 9, 10]. The 2% Gd-doped water is also used as a neutron veto device with which the neutron background can be reduced to 2.2 events per year per tonne of liquid Xenon (LXe)[11].

Gd-doped liquid scintillator (Gd-LS) detectors can not only detect neutron-captured signals but also measure prompt signals caused by neutrons, therefore the neutron tagging efficiency should be higher than those of the Gd-doped hydrocarbon material which only detect neutrons captured on Gd or H and Gd-doped water which only detect neutrons captured on Gd. The background environment for reactor neutrino experiments is similar to direct dark matter searches, and in both cases the backgrounds are produced by cosmic muons and radioactivities in detector components and their surrounding rock. Hence the background shield in reactor neutrino experiments can be utilized for direct dark matter searches. If a WIMP detector with a LXe target (Xe detector) is placed inside the Gd-LS of a reactor neutrino detector, not only can the shielding device of the neutrino detector shield background but the Gd-LS of the neutrino detector can also be used to tag neutrons. However, it seems that more neutron background events are produced in the above experimental configuration:

- The first additional background is from reactor neutrinos. Neutrino detectors are fairly close to nuclear reactors (about 2 kilometers away) in reactor neutrino experiments. A large number of reactor neutrinos will pass through the detectors, and nuclear recoils will be produced by neutrino elastic scattering off target nucleus in the Xe detectors. However, the energies of almost all of these recoils are below 10 keV[12]. If the energy threshold for WIMPs is set to more than 10 keV, the contamination from reactor neutrinos will decrease to a negligible level.
- The second additional background is from low energy neutrons produced by the inverse  $\beta$ -decay reaction  $\bar{\nu}_e + p \rightarrow e^+ + n$ . But their kinetic energies are almost below 100 keV[13], and their maximum energy deposition in the Xe

detectors is as large as a few keV. Thus the neutron contamination can be reduced to a negligible level by the energy threshold of more than 10 keV.

- The third additional background is from cosmic muons. The overburdens in reactor neutrino experiments are only a few hundred meters water equivalent (m.w.e.). For example, the overburden of the far hall in the Daya Bay neutrino experiment is about 910 m.w.e.[14]. In general, the overburdens in underground dark matter experiments are larger than 1500 m.w.e.. Consequently, more neutrons will be produced by cosmic muons in reactor neutrino experiments in comparison with direct dark matter searches. But the muon veto or thick water in reactor neutrino experiments can tag or shield from these neutron events.

So reactor neutrino detectors can be used as neutron veto devices and thus better reject neutron background in underground dark matter experiments.

We designed two experimental configurations in our work. First, four Xe detectors are individually enclosed in four Gd-LS detectors which are used as a neutron veto system (Gd-LS detector veto system). The experimental hall of this experimental configuration is assumed to be located in an underground laboratory with a depth of 2500 m.w.e., which is similar to the Canfranc underground laboratory[15]. Second, four Xe detectors are individually placed inside four reactor neutrino detectors which are used as a neutron veto system (neutrino detector veto system). The experimental hall of the corresponding experimental configuration is assumed to be located in an underground laboratory with a depth of 910 m.w.e., which is similar to the far hall in the Daya Bay experiment. The neutron backgrounds for these two experimental designs are estimated using Geant4[16] simulations.

## 2 Detector description and some features of simulation

Four Xe detectors are individually placed inside four Gd-LS detectors (or the four reactor neutrino detectors) which are used as a neutron veto system. Neutrons will be tagged through neutron interactions with the Gd-LS. Two types of signals can be produced by the interactions: a prompt signal induced by a proton recoil and a delayed signal induced by a neutron captured on Gd or H. So the Gd-LS can be used to shield from and tag neutrons using these signals.

### 2.1 Optimal Gd concentration

Neutrons are captured on Gd with a capture time of about 30  $\mu$ s and on H with a capture time of about 180  $\mu$ s[14], so the neutron-tagged efficiency by Gd is much higher than that by H. In order to minimize the number of neutrons captured on H, the optimal Gd concentration is studied using Geant4 simulations. Only the neutron capture efficiency in the Gd-LS needs to be estimated, whereas the behaviors of neutrons in other sub-detectors do not need to be simulated. Accordingly a 2-meter-high cylinder of radius 1 meter filled with Gd-LS has been simulated, and neutrons with energies up to 10 MeV have been shot from its center. We assume the neutron energy follows a uniform distribution, since the ratio of the neutron captures on Gd and H is neutron energy independent. The results are summarized in Fig. 1. Saturating at a value of about 1%, the neutron capture efficiencies do not change with the Gd concentration, as seen in Fig. 1. Based on this simulation, the Gd concentration in Gd-LS is set to 1% in this work.

## 2.2 WIMP Detection with a Gd-LS detector veto system

A detector with a Gd-LS veto system is designed to simulate a direct detection experiment for WIMPs and estimate the neutron background. The detector configuration is shown in Fig. 2. The detector is located in a cavern of  $40 \times 15 \times 12 \text{ m}^3$  at a depth of 2500 m.w.e.. The four identical cylindrical modules (each 477 cm high and 429 cm in diameter) are immersed into a  $13.6 \times 13.6 \times 9 \text{ m}^3$  water pool at a depth of 2.5 meters from the top of the pool and at a distance of 2.5 meters from each vertical surface of the pool. Each module is partitioned into three enclosed zones. There is one Xe detector in an innermost zone (each 122 cm high and 74 cm in diameter), which is surrounded by the middle zone filled with Gd-LS (1.3 m thick). The outermost zone is filled with transparent mineral oil. 366 8-inch photomultiplier tubes (PMTs) of 8-inch are mounted on the inside of the oil region of the module. These PMTs are arranged in the same way as in Ref.[17], that is, 8 rings of 30 PMTs are on the lateral surface of the oil region, and 5 rings of 24, 18, 12, 6, 3 PMTs are on the top and bottom caps. There is 0.25-tonne LXe used as an active target in each Xe detector. Each Xe detector consists of three components: LXe used as the active target (42 cm high and 51.6 cm in diameter), gaseous Xenon (16 cm high and 51.6 cm in diameter) and liquid Nitrogen used as the cooling system (30 cm high and 52 cm in diameter). The LXe and gaseous Xenon are contained in a copper cylindrical vessel. 61 2-inch PMTs are mounted on the upper gaseous Xenon and other 61 PMTs are mounted under the LXe target. The outer stainless steel tank of each Xe detector is surrounded by an Aluminum reflector for photons produced in the Gd-LS.

## 2.3 WIMP Detection with a neutrino detector veto system

A detector with a neutrino detector veto system is designed to simulate a direct detection experiment for WIMPs and estimate the neutron background. The detector configuration is shown in Fig. 2. The detector is located in a cavern of  $20 \times 20 \times 20 \text{ m}^3$  at a depth of 910 m.w.e.. The four cylindrical reactor neutrino detector modules (414 cm high and 394 cm in diameter) are immersed into a  $13 \times 13 \times 8.5 \text{ m}^3$  water pool (water Cherenkov detector) at a depth of 2.5 meters from the top of the pool and at a distance of 2.5 meters from each vertical surface of the pool. Each module is partitioned into three enclosed zones. The innermost zone is filled with Gd-LS, which is surrounded by a zone filled with unload liquid scintillator (LS). The outermost zone is filled with transparent mineral oil[14]. 366 8-inch PMTs are arranged in the same way as in Ref.[17]. As discussed above in Sec.2.1, the Gd concentration in the Gd-LS needs to be increased to 1% (it should be about 0.1% in reactor neutrino experiments[13, 14, 18]). The four Xe detectors are individually placed inside the four modules, and each Xe detector is surrounded by the Gd-LS in the module. The Xe detectors have the same configuration as those described in Sec.2.2.

## 2.4 Some features of simulation

The Geant4 (version 8.2) package has been used in our simulations. The physics list in the simulations includes transportation processes, decay processes, low energy processes, electromagnetic interactions (multiple scattering processes, ionization processes, scintillation processes, optical processes, cherenkov processes,

Bremsstrahlung processes, etc.) and hadronic interactions (lepton nuclear processes, fission processes, elastic scattering processes, inelastic scattering processes, capture processes, etc.). The cuts for the productions of gammas, electrons and positrons are 1 mm, 100  $\mu\text{m}$  and 100  $\mu\text{m}$ , respectively. The quenching factor is defined as the ratio of the detector response to nuclear and electron recoils. The Birks factor for protons in the Gd-LS is set to  $0.01\text{g}/\text{cm}^2/\text{MeV}$ , corresponding to the quenching factor 0.17 at 1 MeV, in our simulations.

### 3 Background estimation

The recoil energies for WIMP interactions with Xenon nuclei was set to a range from 15 keV to 50 keV[11] in this work. Proton recoils induced by neutrons and neutron-captured signals are used to tag neutrons which reach the Gd-LS. The energy deposition produced by proton recoils is close to a uniform distribution. Neutrons captured on Gd and H lead to a release of about 8 MeV and 2.2 MeV of  $\gamma$  particles, respectively. Due to the instrumental limitations of the Gd-LS, we assume neutrons will be tagged if their energy deposition in the Gd-LS is more than 1 MeV, corresponding to 0.17 MeVee (electron equivalent energy). In the Gd-LS, it is difficult to distinguish signals induced by neutrons from electron recoils, which are caused by the radioactivities in the detector components and the surrounding rocks. But these radioactivities can be controlled to less than 50 Hz according to the Daya Bay experiment[14]. If we assume a 100  $\mu\text{s}$  for neutron tagging time window, the indistinguishable signals due to the radioactivities will result in a total dead time of less than 44 hours per year.

The contamination produced by neutrino events is reduced to a negligible level by the energy threshold of 15 keV[12]. The electron recoil contamination mainly comes from  $^{85}\text{Kr}$  in commercially available Xenon gas (which decays through a beta-decay with an endpoint energy of 678 keV),  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  in PMTs (which decay through gamma and beta decays), and  $^{136}\text{Xe}$  in LXe (which undergoes a double-beta decay with a small probability). In this study, only the electron recoil contamination from Xenon gas and PMTs is considered. We then roughly estimate the electron recoil contamination. According to Bueno et al.[11], the rejection power against electron recoils can reach  $\sim 5 \times 10^{-7}$ . If the concentration of Kr in Xenon gas can be reduced to  $\sim 1$  ppb and the radioactivity from PMTs is assumed to be O(100) events/day[19], as a rough estimation, the total electron recoil contamination is O(0.01) events/(ton·yr). Compared to the neutron background, this electron recoil contamination can be ignored.

Neutrons are produced from the detector components and their surrounding rock. For the neutrons from the surrounding rock there are two origins: first by spontaneous fission and  $(\alpha, \text{n})$  reactions due to U and Th in the rock (these neutrons can be omitted because they are efficiently shielded, see Sec.3.2), and secondly by cosmic muon interactions with the surrounding rock.

We estimated the numbers of neutron background events in the LXe target of one tonne. These numbers have been normalized to one year of data taking and are summarized in Tab.1 and Tab.2.

#### 3.1 Neutron background from detector components

Neutrons from the detector components are induced by  $(\alpha, \text{n})$  reactions due to U and Th. According to Mei et al.[20], the differential spectra of neutron yield can

be expressed as

$$Y_i(E_n) = N_i \sum_j \frac{R_\alpha(E_j)}{S_i^m(E_j)} \int_0^{E_j} \frac{d\sigma(E_\alpha, E_n)}{dE_\alpha} dE_\alpha$$

where  $N_i$  is the total number of atoms for the  $i^{th}$  element in the host material,  $R_\alpha(E_j)$  refers to the  $\alpha$ -particle production rate for the decay with the energy  $E_j$  from  $^{232}\text{Th}$  or  $^{238}\text{U}$  decay chain,  $E_\alpha$  refers to the  $\alpha$  energy,  $E_n$  refers to the neutron energy, and  $S_i^m$  is the mass stopping power of the  $i^{th}$  element.

### 3.1.1 Neutrons from PMTs in copper vessels

The U and Th contaminations in the  $\text{SiO}_2$  material are considered as the only neutron source in the PMTs in our work. Neutrons from  $\text{SiO}_2$  are emitted with their average energy of 2.68 MeV[20]. The total number of the PMTs in the copper vessels of the four Xe detectors is 488. The U and Th concentrations in the PMT components can reach ten or even less ppb[21], so a rate of one neutron emitted per PMT per year is conservatively estimated[11]. Consequently, there are 488 neutrons produced by all the PMTs in the copper vessels per year.

The simulation result in the case of the Gd-LS detector veto system is summarized in Tab. 1. 13.8 neutron events/(ton·yr) reach the LXe target and their energy deposition is in the same range as that of the WIMP interactions, as seen in Tab. 1. Because 0.19 of them are not tagged in the Gd-LS, these background events cannot be eliminated. The simulation result in the case of the neutrino detector veto system summarized in Tab. 2. 14.2 neutron events/(ton·yr) reach the LXe target and their energy deposition is in the same range as that of the WIMP interactions, as seen in Tab. 2. Because 0.22 of them are not tagged in the Gd-LS, these background events cannot be eliminated. The uncertainties of the neutron background from the PMTs in Tab.1 and Tab.2 are from the binned neutron spectra in Ref.[20]. But the neutron background errors from the statistical fluctuation (their relative errors are about 1%) are too small to be taken into account.

### 3.1.2 Neutrons from copper vessels

In the copper vessels, neutrons are produced by the U and Th contaminations and emitted with their average energy of 0.81 MeV[20]. Because each copper vessel is 5 mm thick, its total volume is about  $8000 \text{ cm}^3$ . If we assume a 0.02 ppb U and Th concentrations in the copper material, a rate of one neutron emitted per  $2000 \text{ cm}^3$  per year is conservatively estimated[11]. Consequently, there are 16 neutrons produced by the four copper vessels per year.

The simulation result in the case of the Gd-LS detector veto system is listed in Tab. 1. 0.8 neutron events/(ton·yr) reach the LXe target and their energy deposition falls in the same range as that of the WIMP interactions, as seen in Tab. 1. As 0.02 of them are not tagged in the Gd-LS, these background events cannot be eliminated. The simulation result in the case of the neutrino detector veto system is summarized in Table 2. 0.8 neutron events/(ton·yr) reach the LXe target and their energy deposition falls in the same range as that of the WIMP interactions. As 0.02 of them are not tagged in the Gd-LS, these background events cannot be eliminated. The uncertainties of the neutron background from the copper vessels in Tab.1 and Tab.2 are from the binned neutron spectra in the

Ref.[20]. But the neutron background errors from the statistical fluctuation (their relative errors are less than 1%) are too small to be taken into account.

### 3.1.3 Neutrons from other components

The U and Th contaminations in other detector components also contribute to the neutron background in our experiment setup. Neutrons from the Aluminum reflectors are emitted with the average energy of 1.96 MeV[20]. The U and Th contaminations in the Carbon material are considered as the only neutron source in the Gd-LS/LS. Neutrons from the Gd-LS/LS are emitted with the average energy of 5.23 MeV[20]. The U and Th contaminations in the Fe material are considered as the only neutron source in the stainless steel tanks. Neutrons from the stainless steel tanks are emitted with the average energy of 1.55 MeV[20]. We evaluated the neutron background from the above components using Geant4 simulation. All the nuclear recoils in the LXe target, which is in the same range as that of the WIMP interactions, are tagged. The neutron background from these components can be ignored.

## 3.2 Neutron background due to natural radioactivity in the rock

Water can be used for shielding neutrons effectively, especially in the low energy range of less than 10 MeV. [22]. Additionally, almost all neutrons due to natural radioactivity in the rock are below 10 MeV[11, 21]. The Xe detectors are surrounded by about 2.5 meters of water and more than 1 meter of Gd-LS/LS, so these shields can reduce the neutron contamination from the radioactivities to a negligible level.

## 3.3 Neutron background due to cosmic muons

The total cosmogenic neutron fluxes can be evaluated as a function of the depth for a site with a flat rock overburden[23]. The energy spectrum and angular distribution of these neutrons can be obtained by employing the method in Ref.[23, 24] and the MUSUN code[25]. Fig. 3 shows the energy spectra of the cosmogenic neutrons at a depth of 910 m.w.e. and 2500 m.w.e.. The neutrons are sampled on the surfaces of the caverns, and the neutron interactions with the detector are simulated with the Geant4 package.

The total cosmogenic neutron flux at a depth of 2500 m.w.e. (in the case of the Gd-LS detector veto system) is  $7.52 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$ . Tab. 1 shows that 1.1 neutron events/(ton·yr) reach the LXe target and their energy deposition is in the same range as that of the WIMP interactions. But all of them are tagged by the Gd-LS. Because of that the neutron background from cosmic muons can be ignored. The total cosmogenic neutron flux at a depth of 910 m.w.e. (in the case of the neutrino detector veto system) is  $1.31 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ . Muon veto systems can tag muons very effectively, thereby most cosmogenic neutrons can be rejected. For example, using the muon veto system, the neutron contamination level could be reduced by a factor of about 10[21]. In the Daya Bay experiment, the contamination level can even be reduced by a factor of more than 30[14]. Tab. 2 shows that 26 neutron events/(ton·yr) reach the LXe target and their energy deposition is in the same range as that of the WIMP interactions. 0.4 of them are not tagged by the Gd-LS/LS. We conservatively assume the neutron contamination level from cosmic

muons decreases by a factor of 10 using a muon veto system. This could lead to the decrease of cosmogenic neutron contamination to 0.04 events/(ton·yr). The uncertainties of the cosmogenic neutron background in Tab.1 and Tab.2 are from the statistical fluctuation.

### 3.4 Total Background

According to our simulations, if the detector is located in an underground laboratory at a depth of 2500 m.w.e., the neutron background is mainly from the PMTs and copper vessels, and the total background is  $0.21 \pm 0.03$  events/(ton·yr) (see Tab.1). If the detector is located in an underground laboratory at a depth of 910 m.w.e., the neutron background is mainly from the PMTs, copper vessels and cosmic muons, and the total background is  $0.28 \pm 0.05$  events/(ton·yr) (see Tab.2).

## 4 Conclusion and discussion

The neutron background can be effectively suppressed with the Gd-LS or neutrino detector used as the neutron veto system in direct dark matter searches. Tab. 1 and Tab. 2 show the total neutron contaminations in the cases of the Gd-LS veto system and neutrino detector veto system are 0.2 and 0.3 events/(ton·yr), respectively. The neutron background events are caused by two sources:

- After interacting with the LXe nucleus, a part of neutrons are absorbed by the components within the Xe detector. Most of the neutrons are absorbed by the liquid nitrogen in the cooling system, and a few of the neutrons are absorbed by the copper vessels and steel tanks in the Xe detector. These neutrons cannot deposit their energy in the Gd-LS and thus are misidentified as WIMP signatures.
- The other neutrons deposit a part of energy in the Gd-LS after interacting with the LXe nucleus, but their energy deposition is below the energy threshold of 1 MeV. Hence these neutrons are misidentified as WIMP signatures.

If no signals are significantly observed, sensitivities to WIMP-nucleon spin-independent elastic scattering can be calculated via the same method as Ref.[26]. To evaluate these sensitivities, we assume a standard dark matter galactic halo[3], an energy resolution that amounts to 25% for the energy range of interest and 50% nuclear recoil acceptance. Our calculation shows that an exposure of one tonne  $\times$  year could reach a cross-section of about  $6 \times 10^{-11} pb$  at the 90% confidence level (see Fig.4). We note some updated results for dark matter searches: the CDMSII experiment and XENON100 experiment have given the upper limits on the WIMP-nucleon spin-independent cross-section of  $3.8 \times 10^{-8} pb$  for a WIMP of mass 70 GeV/ $c^2$  and  $7.0 \times 10^{-9} pb$  for a WIMP of mass 50 GeV/ $c^2$  at the 90% confidence level, respectively[5, 27].

Compared to Ref.[11], the neutron background in the present paper decreases by a factor of about 10. Especially in the case of the neutrino detector veto system, after finishing a precision measurement of the neutrino mixing angle  $\theta_{13}$ , we can utilize the existing experiment hall, background shield and veto, Gd-LS and so on. This will not only save substantial cost and time for direct dark matter searches, but the exclusion limit for the experimental configuration could also reach about  $6 \times 10^{-11} pb$  at the 90% confidence level (one tonne  $\times$  year).



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Tab. 1: Estimation of neutron background from different sources for an underground laboratory at a depth of 2500 m.w.e. The column labeled " $15\text{keV} < E_{\text{recoil}} < 50\text{keV}$ " identifies the number of neutrons whose energy deposition in the LXe is in the same range as WIMP interactions. The column labeled "Not Tagged" identifies the number of neutrons which are misidentified as WIMP signatures (their energy deposition in the LXe is in the same range as WIMP interactions while their recoil energies in the Gd-LS are less than the energy threshold of 1 MeV). The row labeled "PMTs in copper vessels" identifies the number of neutrons from the PMTs in the copper vessels. The row labeled "copper vessels" identifies the number of neutrons from the copper vessels. The row labeled "cosmic muons" identifies the number of cosmogenic neutrons. The terms after  $\pm$  are errors.

	$15\text{keV} < E_{\text{recoil}} < 50\text{keV}$	Not Tagged
PMTs in copper vessels	$13.8 \pm 2.21$	$0.19 \pm 0.030$
copper vessels	$0.8 \pm 0.15$	$0.02 \pm 0.003$
cosmic muons	$1.1 \pm 0.10$	$< 0.01$
total	$15.7 \pm 2.2$	$0.21 \pm 0.03$

Tab. 2: Estimation of neutron background from different sources for an underground laboratory at a depth of 910 m.w.e. The row labeled "cosmic muons" identifies the number of cosmogenic neutrons in the case of not using the muon veto system. The row labeled "muon veto" identifies the number of cosmogenic neutrons in the case of using the muon veto system. The other columns and rows in this table are of the same meaning as in Tab. 1. We assume that neutron contamination level from cosmic muons decreases by a factor of 10 using a muon veto system. Only the total background in the case of using the muon veto system is listed in this table. The terms after  $\pm$  are errors.

	$15\text{keV} < E_{\text{recoil}} < 50\text{keV}$	Not Tagged
PMTs in copper vessels	$14.2 \pm 2.72$	$0.22 \pm 0.035$
copper vessels	$0.8 \pm 0.15$	$0.02 \pm 0.003$
cosmic muons	$26.0 \pm 3.2$	$0.4 \pm 0.4$
muon veto	$2.6 \pm 0.32$	$0.04 \pm 0.04$
total (muon veto)	$17.6 \pm 2.7$	$0.28 \pm 0.05$

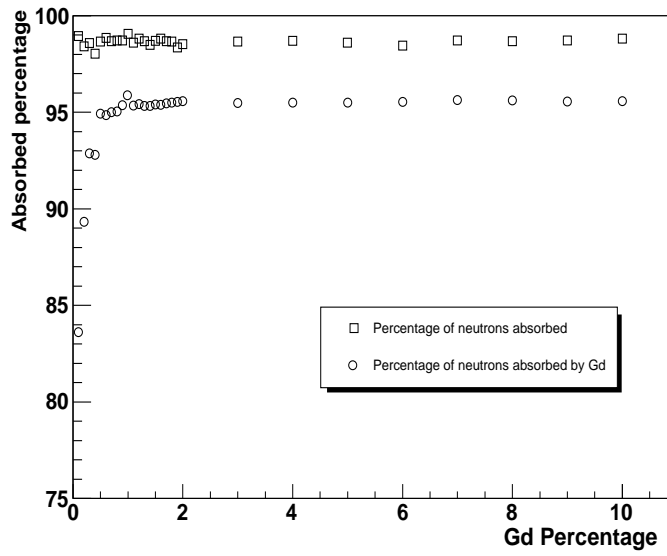


Fig. 1: Percentage of absorbed neutrons as a function of the Gd concentration. The squares denote the total neutron-absorption efficiencies of Gd-LS and the circles denote the neutron-absorption efficiencies of Gd.

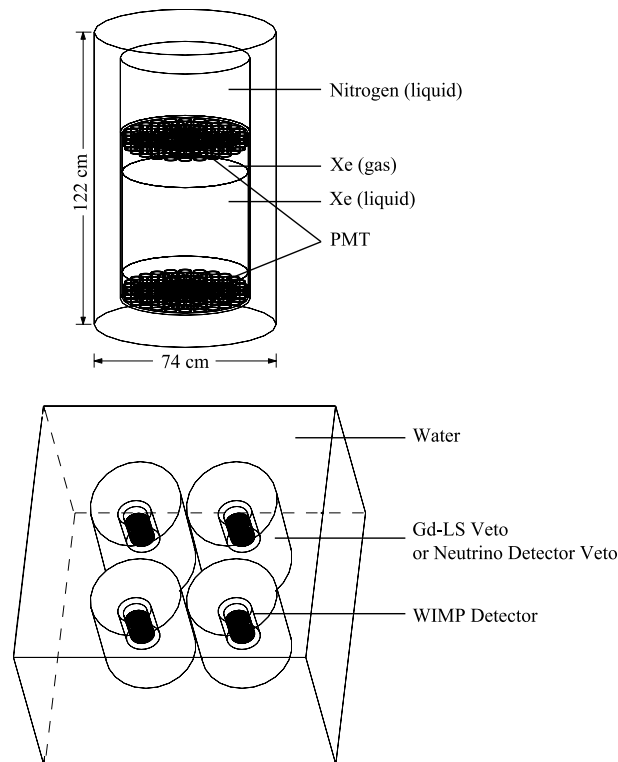


Fig. 2: Top: WIMP detector with a LXe detector (Xe detector). Bottom: four Xe detectors individually placed inside four Gd-LS detectors or four neutrino detectors in a water shield.

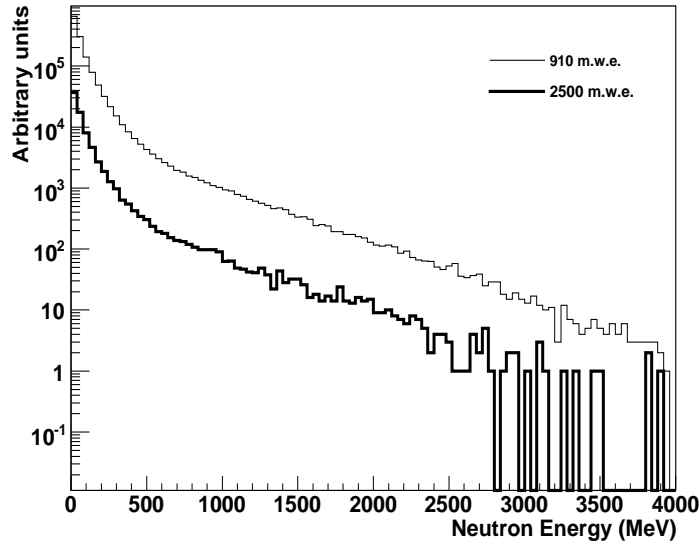


Fig. 3: The energy spectra of cosmogenic neutrons at depths of 910 m.w.e. and 2500 m.w.e.

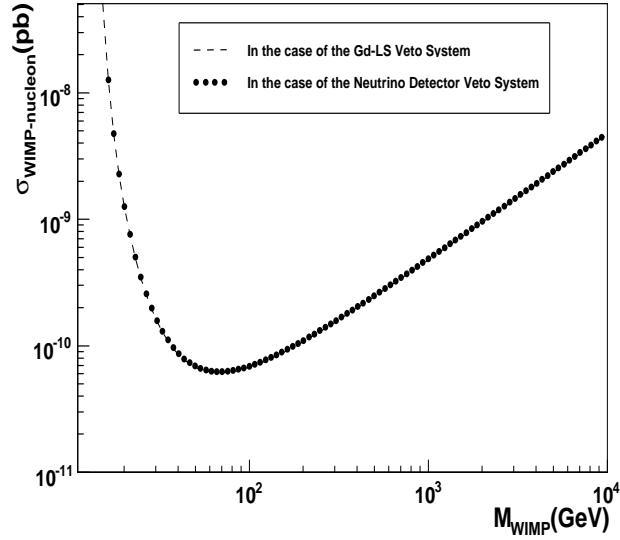


Fig. 4: We calculate the sensitivities to spin-independent WIMP-nucleon elastic scattering assuming an exposure of one tonne  $\times$  year. The calculation shows this exposure could reach a cross-section of about  $6 \times 10^{-11} pb$  at the 90% confidence level. The tool from Ref.[28] has been used.